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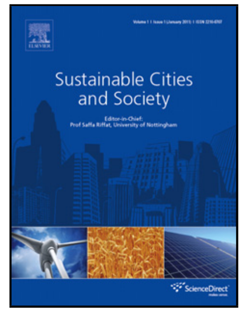

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A performance evaluation of future low voltage grids in presence of prosumers modelled in high temporal resolution

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Highlights

- Methodology for generating 1-minute load profiles from 1-hour readings of from smart meters
- Framework for power system impact analysis of the LV network in residential communities.
- Low voltage network under the presence of different penetration levels of prosumers
- Energy infrastructure of future communities and/or cities will have different nature and time occurrence
- Risk for originating disturbances such as flicker at the user level is significant

Abstract

Prosumers have a different interaction with the distribution network in comparison with traditional consumers. They have a bi-directional power exchange with the grid, meaning they receive from as well as deliver electricity to the network. The emergence of prosumers is expected to challenge the way network operators control the residential low-voltage (LV) distribution networks. Commonly, the metering of received and delivered electricity at the residential level is conducted on 1-hour basis, thus only hourly load/generation profiles are available for the system operators to conduct the power system impact analysis. Yet, it is relatively difficult to have an accurate prediction of the real system performance if the intra-hour phenomena are not considered. A better estimation requires employment of higher temporal resolution profiles during the power system studies. To address these challenges, which future smart cities and communities might face, this paper presents a methodology for generating 1-

minute load profiles based on the hourly readings from smart meters. Secondly, it demonstrates gain in information about LV network by employing the high resolution profiles for power system impact analysis. Finally, it highlights the problems of smart residential networks with high share of prosumers for two LV network scenarios during winter and summer weeks.

Key words: **Domestic load profiles, Methodology for resolution change, Energy efficient buildings, Distributed energy generation, Management of smart grids**

NOMENCLATURE:

Subscripts

a	appliance, e.g. washing machine, TV, PC
w	week number
h	hour of the day
d	day of the week (weekday or weekend),
n	number of occupants,
c	type of occupants,

Acronyms

BL	base load
COP	coefficient of performance (-)
CteZ	constant impedance
CteP	constant power
DSO	distributed system operator
HP	heat pump
LV	low voltage
NOCT	nominal operating cell temperature
PEV	personal electric vehicle
PV	photovoltaic panels
ST	transformer station
STC	standard test conditions

Variables

A	PV module area (m^2)
cosϕ	power factor (-)
f	frequency of use of appliance (times/day)
F_{soc}	social random factor (-)
I	global incident radiation on an arbitrarily oriented plane (W/m^2)
I_{NOCT}	global incident radiation at nominal operating cell temperature (W/m^2)
L_{lmax}	loading of the maximum loaded power line in the LV system (p.u.)
L_{st}	loading of the transformer station (p.u.)
μ	temperature coefficient of PV module output power ($1/^oC$)
η_{mp}	PV module maximum-power-point efficiency (-)
$\eta_{PVsystem}$	efficiency of the photovoltaic system, including cell, wiring and inverters (-)
η_{STC}	PV module conversion efficiency at (STC) (-)
P_{act}	probability to have activity (-)
$P_{LVcustomer}$	probability of consuming the electricity for specific domestic customers (-)
P_{on}	probability of starting the appliance (-)
P_{season}	seasonal probability (-)
P_{st}	active power measurement at the transformer station level (MW)
P_{STC}	power output of PV module at STC (W)
P_{step}	scaling factor depends Δt (-)
P_{rt}	nominal rotated power (kW)
ΣP_{hp}	aggregated power consumption from all the HP units across the LV grid (kW)
ΣP_{pv}	aggregated power generation from all the PV units across the LV grid (kW)
R	resistance of power line (Ω/km)
t_{cycle}	cycle period length of appliance (minute)
t	time interval index
Δt	time interval length (1-minute, 15-minutes, hour)
T_o	outdoor temperature (^oC)
$T_{c,STC}$	cell temperature at STC (^oC)
$T_{c,NOCT}$, $T_{a,NOCT}$	cell and outdoor temperature at the NOCT (^oC)
V_{max}, V_{min}	maximum and minimum voltage across the LV network (p.u.)
X	inductive reactance of power line (Ω/km)

1. Introduction

As a follow-up to the energy agreement from March 2012, the Danish Energy Agency (DEA) has developed five technically consistent models of the future energy supply, which are the Danish roadmap towards sustainable and fossil-fuel-free society. These models meet the political targets of a fossil-fuel-free power and heat network in 2035 and fossil-fuel-independence of the energy system in 2050 (*Energiscenarier frem mod 2020, 2035 og 2050*, 2014). In most of scenarios massive electrification of the energy system is foreseen, on the supply as well as on the demand side. For example in the building sector, it is predicted that individual heat pumps (HPs) supply 31% and 45% of heat demand in 2035 and 2050, respectively. When zooming in on the supply side, the photovoltaic (PV) capacity is expected to increase by factors 2 and 4 in 2035 and 2050, respectively with 2014 as reference. Moreover, according to the IEA PVPS statistics 61% of the total PV installed capacity in Denmark is found at the domestic level (PV units ≤6 kW) (Ahm, 2013). From this is derived that the power system, and in particular the LV network, will have to accommodate a bulk of power load coming from the electrification of heat demand as well as be able to manage high fluctuations of decentralized PV. These changes impose new challenges on the LV grid management, such like grid operation at its "edge", increasing energy consumption at peak periods, consolidation of operating units resulting in rise of "footprints" and more complex problems with shorter decision times and smaller error margins (Moslehi & Kumar, 2010). They also may lead to limitations of the amount of exported energy for building owners, e.g. Germany has already enforced restrictions on private PV generation exported to the grid (Wirth, 2018).

The building sector has faced important changes in the past decades due to the tightening of the building regulation and to the emergence of new technologies. In the early 1990s, the first passive houses with well-insulated and air-tight envelopes were designed to decrease the energy use of buildings (Feist, Wolfgang, Peper, Søren, Görg, 2001). At the start of the new century (2010), the concept of net Zero Energy Buildings (nZEB) started to spread (Krarti & Ihm, 2016; Marszal et al., 2011; Miller & Senadeera, 2017; Mohamed, Hasan, & Sirén, 2014; Salom, Marszal, Widén, Candanedo, & Lindberg, 2014; Sartori, Napolitano, & Voss, 2012). The nZEB is commonly called a prosumer, as it consumes as well as generates energy. This means that there are periods when the building acts as a producer, i.e. the energy generation of a building is higher than its consumption and thus the building delivers surplus energy to the network. In the opposite situation, the building acts as a traditional energy consumer. The PV is the most common technology applied for distributed energy generation at the single building and community level (Hachem-Vermette, Cubi, & Bergerson, 2016; Mohamed, Hamdy, Hasan, & Sirén, 2015; Rahmani-Andebili, 2017; Voss & Musall, 2012; Widén, Wäckelgård, Paatero, & Lund, 2010b) and in Denmark the PV combined with the HP is the cost-optimal configuration of residential energy supply system (H. Lund, Marszal, & Heiselberg, 2011; Marszal, Heiselberg, Lund Jensen, & Nørgaard, 2012; Milan, Bojesen, & Nielsen, 2012). In this sense, the electricity consumption or generation technologies selected at the domestic level can be combined in different ways to define a prosumer or non-prosumer, i.e. i) HP and PV, ii) only HP or only PV, iii) neither HP nor PV. In consequence, the net profiles will significantly differ between consumers. These profiles are not commonly employed during the traditional design and planning studies carried out by the local distributed system operators (DSOs). What is more, various penetration levels of PV and/or HP and their distribution across the local LV network will have a significant influence on the system performance (De Cerio Mendaza, Bak-Jensen, Chen, & Jensen, 2014; Widén et al., 2010b). Therefore, since the configuration of residential distribution grids is becoming more and more complex, and the infrastructure congestion should be avoided by any mean, the planning and design of the future LV networks require a precise and realistic representation of their future performance.

Various studies have proposed different measures to increase the match between the generation and demand profiles at the single prosumer level, e.g. individual batteries or flexible demand (Cao, Hasan, & Sirén, 2013; Rahmani-Andebili, 2017; Widén, Wäckelgård, & Lund, 2009). Yes, in this paper the authors argue that implementation of batteries at the individual building level is not economically feasible solution compared to the measures that could be applied at the aggregated level, such as integration of different energy sector, usage of thermal energy storages, and utilization of batteries from electric vehicles (EVs) (Henrik Lund, Østergaard, Connolly, & Mathiesen, 2017; Mathiesen et al., 2015). Furthermore, as highlighted in (McKenna, McManus, Cooper, & Thomson, 2013; McManus, 2012) the batteries in grid-connected domestic PV systems have negative environmental impact and should not be promoted in future low carbon energy systems. Although the demand respond programs are well recognized solutions to solve the future operational bottlenecks of the LV networks (Mirakhorli & Dong, 2018), the authors have consciously left them outside of the scope of this study, in order to investigate the influence of different mix of prosumers and non-prosumers on the grid performance and clearly identify the worst-case scenario for these residential districts and thereby even stronger highlight the need for customers/homeowners active engagement in successful transition towards fossil free society.

Nowadays, it is a common practice among DSOs and network planning engineers to use one-hour based power consumption data to model the behavior of specific consumers in their system studies. This resolution is the metering resolution which is normally employed for energy billing purposes. This is also frequently used by the consultancy engineers while analyzing the results of building energy performance. However, this is an averaged solution that differs significantly from how the pro/consumer behavior is in reality, especially during the intra-hour (Dickert & Schegner, 2010). As stated in (Widén, Wäckelgård, Paatero, & Lund, 2010a), 10-minute based resolution is recommended in system studies aiming to assess the impact of PV integration on the LV networks in order to get a fair picture of its performance. In (Wright & Firth, 2007) instead, authors concluded that only with 1-min based resolution data it is possible to capture most of the phenomena and particularities induced at the household point of connection (POC) due to the electricity use and onsite generation. In this sense, such resolution becomes essential for obtaining a realistic picture of the local distribution networks performance.

The tools and models to facilitate the research activities related to residential LV networks and the influence of various demand side respond strategies have been developed both by building and network research environments (Pedrasa, Spooner, & MacGill, 2010; Pipattanasomporn et al., 2012; Richardson, Thomson, Infield, & Clifford, 2010; Stokes, 2005; Torquato, Shi, Xu, & Freitas, 2014; Widén & Wäckelgård, 2010). All models have their own purpose, namely either to simulate, in the best possible way, the occupants' use of household appliances in a given local context and thus determine power load profiles (Richardson et al., 2010; Stokes, 2005; Widén & Wäckelgård, 2010), or to enhance the studies of the LV network performance (Pedrasa et al., 2010; Pipattanasomporn et al., 2012; Torquato et al., 2014). However, these tools often reflect cultural specific inputs of the country/region for which they are developed, (e.g. set of household appliances, daily behavioral routines, weather conditions, network configuration, infrastructure characteristics) and thus cannot be directly applied in other circumstances. Moreover, the network studies often compromise the input data on the building occupants or include a generic network configuration. This paper attempts to narrow this gap by applying an empirical-probabilistic model, which correlates power consumption with sociocultural factors, e.g. size of the family, occupants' approach to the energy use/savings, to determine load profiles and by performing the power system impact analysis based on a real residential LV network located in northern Denmark.

Based on the importance of what is previously stated, this paper has three main objectives. Firstly, it presents the transformation procedure of 1-hour readings of power use from the individual customers to higher temporal resolution using a combination of the actual 1-hour electricity demand profiles, appliance data and customized empirical-probabilistic model. Secondly, it demonstrates how much extra information is gained about the LV network performance when using the high resolution profiles for power system impact analysis. Finally, it highlights the problems of the future residential distribution networks with a high share of prosumers for two LV network scenarios that are developed based on the DEA guidelines for the energy system outlook in 2035 and 2050. Moreover, due to a significant seasonal variations in PV power generation in high latitude locations, we investigate network performance for a winter and summer week. To sum up, the overall contribution of this paper is to draw attention to the fact that due to the complexity of the future local LV network the power system impact analysis will require high resolution inputs in order to get a full and realistic picture of the network performance and thus be able to facilitate network designers in identifying potential solutions to overcome given operation bottlenecks.

The paper is organized as follows. Section 2 introduces briefly the empirical-probabilistic model and the transformation procedure employed for increasing the temporal resolution of base load profiles, describes the modeling of heat pump in two prosumers topologies, and briefly presents methodology used for creating PV generation profiles. Section 3 describes the Danish

LV network and the case studies considered for carrying out the simulations. Section 4 summarizes the results obtained and finally section 5 discusses the conclusions.

2. Methodology and implementation

The analysis is conducted in two stages, see Fig. 1. Firstly, high resolution profiles of BL, HP load and PV generation are created. Secondly, the one-minute load and generation profiles are implemented in the LV grid model and the network performance for given scenarios is assessed.

2.1. *Domestic base load* (BL)

2.1.1 Empirical-probabilistic plug-loads model

The one-minute profiles of domestic base load are created using the empirical probabilistic behavior model developed by Marszal-Pomianowska et al. (A. Marszal-Pomianowska, Heiselberg, & Kalyanova Larsen, 2016). The model has already been applied in the dynamic building simulations domain (Le Dréau & Heiselberg, 2016; Anna Marszal-Pomianowska, Stoustrup, Widén, & Le Dréau, 2017). The model employs the "bottom-up" modeling approach by piecing together the individual appliance characteristics and its cycle of power use to form the total electricity demand profile of a household. It is developed in Matlab environment and validated to generate BL profiles of the Danish single-family houses. It accounts for the correlations between the electricity use and the number of occupants in household as well as the occupants' attitude towards energy use/savings (interested, neutral, disinterested), the seasonal long-term variations in electricity as well as the short and/or sudden variations due to weather fluctuations (like heavy rain or very sunny winter afternoon) affecting the washing needs and/or the lighting, local or international events (e.g. TV shows or energy-saving initiative effecting the time of using household entertainment devices). All of these connections are put together in the formula presented in Eq. 1 and the procedure to generate the profiles is as follows.

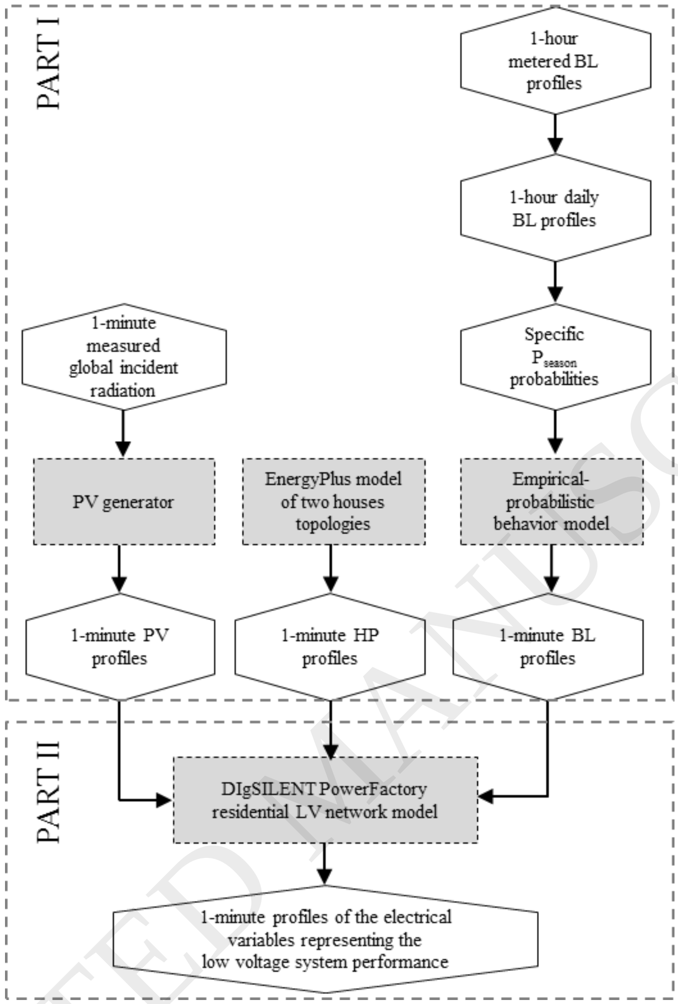


Fig.1 Overview of the methodology

Firstly, the number of occupants and their attitude towards energy savings is given for each house. These inputs together with the penetration level specified for each appliance are the background data for equipping each customer with a set of appliances. Secondly, the model generates the electricity load profile individually for each appliance. To do so, for each minute, a random number P is generated between 0 and 1 and then P_{on} is calculated using (1). P_{on} also varies between 0 and 1 and defines whether or not the appliance switches ON. When the switch ON event occurs at the time step t, $P_{on} > P$, the operation cycle starts and therefore the cycle of power consumption is added to the load profile of the appliance. The operation cycle finishes at time t + t_{cycle}. During the time the appliance is ON the P_{on} is not calculated. F_{soc} is a social random factor, which accounts for short-term and sudden variations of the household electricity use, P_{season} models the sinusoidal pattern of the seasonal, long-term variations in household electricity use.

$$P_{on}(a,w,h,d,n,c,\Delta t) = P_{act}(a,h,d)f(a,d,n,c)F_{soc}P_{season}(w)P_{step}(\Delta t) \qquad (1)$$

Finally, by summing up the power demands of all appliances installed within a given household the total power profile for the given household is generated. As illustrated in Fig. 2, the model normally operates with 1-minute resolution; however, profiles of lower frequency resolution, e.g. ten minutes or one hour, can also be created.

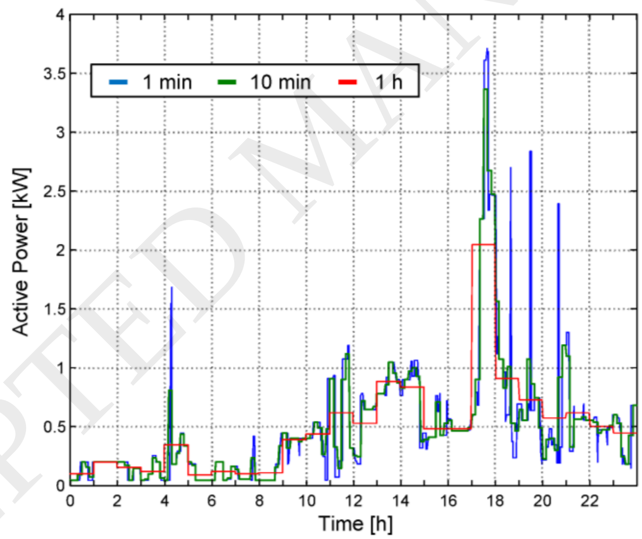


Fig. 2 Comparison of profiles with different resolution.

2.1.2 Transforming the 1h load profiles to higher temporal resolution – procedure overview

The 1-minute profiles for BL are created to match the real 1-hour metered power consumption of each specific domestic consumer and thus to the best possible way reflect the real LV network loading situation. The conversion was a 3-stages process and the specifics are as follows.

1. Determination of the size of household and its attitude towards energy use/savings.

As no data on the customers is available the first step involves estimating the number of occupants in the house. This is done by dividing the annual household electricity consumption by the average electricity consumption of 1600 kWh/year per occupant ("PrivateBoligen," n.d.). In the same way, the attitude of the occupants towards energy savings is not given, so consumers representing a neutral approach were assigned to all households.

2. Composition of the appliances

The input parameters from stage 1 are used to define the set of appliances for each customer. This is done on a random basis using the penetration rates given for each appliance (Table A1 in (A. Marszal-Pomianowska et al., 2016)) with a condition that the annual household electricity demand must be within specified limits depending on the number of occupants, see Eq. (2). When assigning the specific appliances, the attitude of customers towards energy use is not taken into consideration. For each selected appliance, an annual electricity demand is calculated and the sum of these gives the annual electricity demand of a customer (building).

$$1988 + 773{,}6 \bullet \text{number of occupants [kWh/year]}\_ \quad (1)$$

3. Customization of the empirical-probabilistic model.

3a. Calculation of probabilities of consuming the electricity for specific domestic customers ($P_{LVcustomer}$)

The seasonal probability - P_{season} - and the social random factor - F_{soc} - reflect the average Danish household and thus cannot be used when generating a 1-minute profile of a specific customer. The 1-hour metered power use profiles encompass the whole year data for individual customer; therefore, it is possible to include both the seasonal variations and household specific behavior in a single variable. The probability is calculated as the hourly consumption normalized by the daily use.

3b. Changes in the model

The probabilities from step 3a - $P_{LVcustomer}$ - are incorporated in the model (see Eq.(3)) in order to produce a 1-minute resolution electricity profile for each appliance, which aggregated gives the yearlong high-resolution electricity demand profile for individual LV network customer.

$$P_{on}(a,w,h,d,n,c,\Delta t) = P_{act}(a,h,d)f(a,d,n,c)P_{LVcustomer}(h)P_{step}(\Delta t) \qquad (2)$$

The means of generating a 1-minute profile is briefly described in section 2.1.1 and in detailed in (A. Marszal-Pomianowska et al., 2016). Fig. 3 depicts the output of the described methodology, i.e. the original 1-hour electricity load profiles provided by the utility and the corresponding 1-minute profiles generated by applying the proposed methodology.

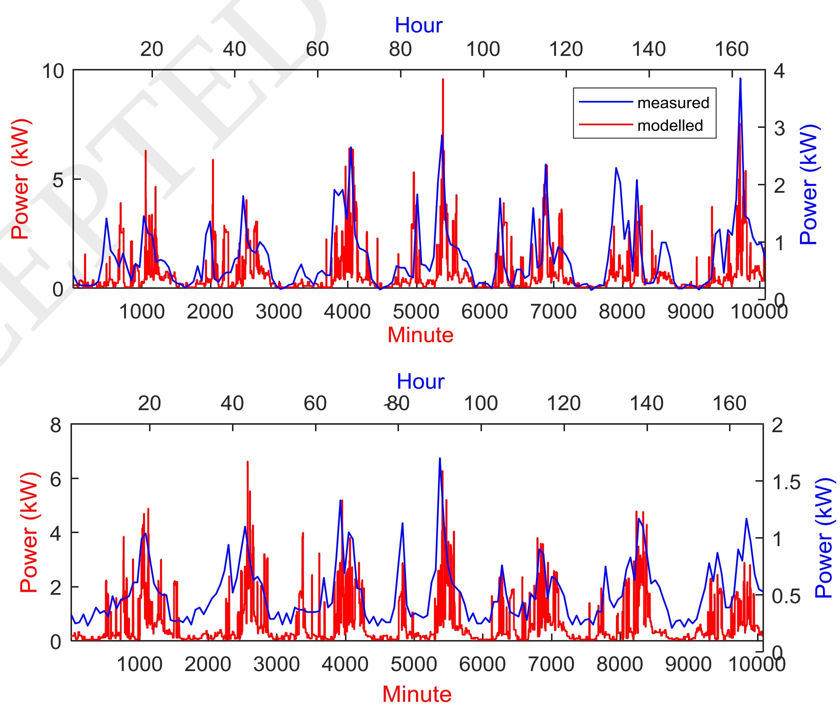


Fig 3. Modelled 1-minute and measured 1-hour end-use load profiles in 2 households during a winter week.

2.2. Heat pump load

In order to create the one-minute consumption profiles for the HP loads two types of residential buildings are considered: a typical single-family house from the 1980s and a passive house. The first building, denominated in Danish as “Parcelhus”, represents a typical building from the 1980s, made of bricks and characterized by its relatively poor thermal performances (yearly heating need around 155 kWh/m^{2}year). The second single-family house is the “KomfortHus” and has been built according to the Passive House standard (yearly heating need of 13 kWh/m^{2}year). The building is airtight, highly insulated with 55 cm of stone wool and characterized by light external walls and a heavy concrete core. Fig. 4 presents an illustration of these two buildings, and more detailed description about them can be found in (Kragh & Wittchen, 2014; Le Dréau & Heiselberg, 2016). The simulations of the building and its occupants are performed using EnergyPlus (“EnergyPlus software,” n.d.).

Fig. 4 Building types: a) building from the 1980s, b) Passive House

In order to heat up these houses, two types of emitters are considered: radiators in the 1980s house and underfloor heating in the passive house. These emitters are linked to a ground-source heat pump with vertical boreholes located at 100 m depth where the soil temperature is stable (equal to 10°C). The ground-loop heat exchanger model uses a set of non-dimensional temperature response factors - g-functions - which allows the for calculation of the temperature change at the borehole wall in a response to a step heat input [20]. The heat pump is sized to cover the annual heat demand only for space heating and the heat demand for the domestic hot water is accounted in a simplified manner, i.e. hourly consumption profiles for an average Danish family with DHW consumption of 40l/day per person are included in the model (Jensen, Nørgaard, Daniels, & Justesen, 2011).The heat pump delivers hot water to the building at different temperatures depending on the types of emitter and building (ranging from 30°C up to 70°C). The nominal Coefficient of Performance (COP) of the heat pump is 4.5 (1980s house) and 4.95 (passive house). The heat pump model uses manufactures published data to find the required parameter values for each component. The parameters are determined using a multi-variable optimization algorithm (Fischer, Wolf, Scherer, & Wille-Haussmann, 2016). The result extracted from the simulations is the total electricity use for heating, which accounts for both the electricity for the heat pump and also for pumps.

2.3. Rooftop photovoltaic generator

The high resolution generation profiles from rooftop photovoltaic are obtained for a typical PV installation located in Denmark defined by the Danish Technological Institute (DTI), see Table 1.

Table 1. Characteristics of PV module according to DTI

Area [m^2]	**Slope[deg]**	**Orientation**	**PV efficiency [%]**
40	30	South	14

The power output P_{PV} is calculated using the following general expression

$$P_{PV} = A_c I \eta_{mp} \eta_{PVsystem} \qquad (3)$$

The global incident radiation on an arbitrarily oriented plane is calculated from incident beam and diffuse radiation onto the horizontal plane measured in 1-minute resolution using the transposition models outlined in (Duffie & Beckman, 2013). In this case, $\eta_{PVsystem}$ is assumed constant but the η_{mp} is assumed temperature dependent and calculated according to

$$\eta_{mp} = \eta_{STC}\left[1 + \mu(T_o - T_{c,STC} + I\frac{T_{c,NOCT} - T_{a,NOCT}}{I_{NOCT}}(1 - \eta_{STC})\right] \quad (4)$$

Knowing the measured size of module $A$and an output P_{STC} at STC of this module, η_{STC} is found using following formula:

$$\eta_{STC} = \frac{P_{STC}}{I_{STC}A} \quad (5)$$

Table 2 shows the parameters used for the PV model developed in order to create the 1-minute resolution profiles for this distributed generation technology.

Table 2. Parameters of PV model employed

μ [ºC^{-1}]	**$T_{C,STC}$ [ºC]**	**$T_{C,NOCT}$ [ºC]**	**$T_{a,NOCT}$ [ºC]**	**I_{NOCT} [W/m^2]**
-0.005	25	46	20	800
P_{STC} [W]	**I_{STC} [W/m^2]**		**A [m^2]**	**$\eta_{PVsystem}$ [%]**
140	1000		1	85

3. Test system and case of study

This section introduces the model of the typical Danish LV grid and the cases of study considered for performing the corresponding simulation. The implementation of the network model as well as all the technical assessment has been performed using the technical platform, DIgSILENT PowerFactory.

The selected test system is a LV network currently under operation in the northern part of Denmark. The area where it is located is characterized by the non-availability of district heating service, which implies that the heating requirements of the users are currently satisfied with old fashion heating systems. This specific situation and the foreseen scenario of a fully renewable energy system make likely the emergence of HPs and PVs across the network in the future. The existing 137 private consumers are supplied with electricity through a 315 kVA 20/0.4 kV transformer and a seven-string radial network. The fully detailed single-line diagram and any relevant parameters about this piece of infrastructure such as the R/X values of the grounded cables or the transformer station (ST), characteristics are presented in the Appendix and further information is also available in (De Cerio Mendaza et al., 2014). This technical assessment, which focused more on the steady state (static) part of the power system analysis, aimed at defining the hosting capability of such network in presence of HPs and plug-in electric vehicles (PEV). The results show that depending on how the load is distributed across the LV system, its performance can vary significantly finding that even new low load penetration levels could induce grid-congestion during peak moments of the day.

In this case instead, it is in the authors' interest to evaluate the dynamic performance of the LV network under the presence of different penetration levels of prosumers. Each consumer is modeled in the selected simulation tool by two loads - one for the base load and the other for the HP load- and a static generator which represents the PV unit. The BL is characterized as a mix of constant impedance (CteZ) and constant power load (CteP), and the HP unit is characterized as the constant power load (Willis, 2004). Table 3 provides the parameters utilized to describe the different load and generation models during the analysis. To define the voltage dependency according to the active power consumption of the different loads a typical ZIP modeling approach has been employed (Kundur, 1994). Furthermore, depending on the individual integration level and their distribution across the network, the HP and PV units will be activated or de-activated among the different pro-/consumers.

Table 3. Features of loads & generators

Load	Parameters			
	Cte Z	Cte P	P_{rt} [kW]	cosϕ [-]
BL	0.3	0.7	data	0.95(ind)
HP	-	1	2	0.98 (ind)
PV	-	-	6	1 (-)

The household in possession of both units will be considered as prosumers. On the other hand, those users in possession of either of them or only with one of them will be just considered as non-prosumers. At this point, it is important to mention that in the random assignation of HPs and PVs among the different users, those assigned first with a HP will have a higher chance to be assigned with a PV unit taking into account the investment trend given in Denmark nowadays in this sense. Based on the stated and the energy scenarios foreseen by the DEA several cases of study are contemplated for realistic representation and comparison of the future dynamic performance of such infrastructure. These are listed and briefly described below:

– *Case I - Base Case:* It represents the current status of the LV network where only the base load is present.
– *Case II - DEA 2035 scenario:* It aims to capture and reflect the system integration levels expected by 2035. Accordingly, 50% of HP and 25% of PV penetration are considered resulting in the fact that 25% of the households are classified as prosumers.
– *Case III - DEA 2050 scenario:* It intends to capture and reflect the system integration levels expected by 2050. Accordingly, 100% of HP and 50% of PV penetration are considered resulting in the fact that 50% of the households are classified as prosumers.

As a simple remainder, the criteria utilized for evaluating the LV network performance during its assessment are framed according to DSO experiences. In terms of voltage, even though the European standard EN 50160 defines that the voltage at every bus of the medium voltage (MV) and LV network should be within ±10% of its nominal value, a more conservative value of a ±6% is considered in this case as this is the common threshold used in practice by the DSO (De Cerio Mendaza, Szczesny, Pillai, & Bak-Jensen, 2016). Further, they also say that the voltage for a single customer should not deviate more than 10% over a day (difference between maximum and minimum). In terms of the infrastructure loading, a maximum limit of 80% is set for both the ST and the underground cables.

4. Transformation procedure – verification and output

The verification of the transformation procedure focus on ensuring that the created high-resolution profiles follow the original metered profiles and hence the proposed methodology gives valuable inputs for future LV network performance analysis. Moreover, the results are also compared with other research studies on electricity consumption in Danish households.

Fig. 5 depicts the hourly load profiles of the measured and modelled end-use load profiles for 4 houses during a winter and summer week. The comparison is done for the hourly data, since this is the resolution of the metered data. A close overall correspondence can be observed for all four households during both seasons, although the modelled loads have higher peaks then the measured load curves. This could be because occupants have more energy efficient appliances then the ones used in the model, which represent the average appliances for the Danish household.

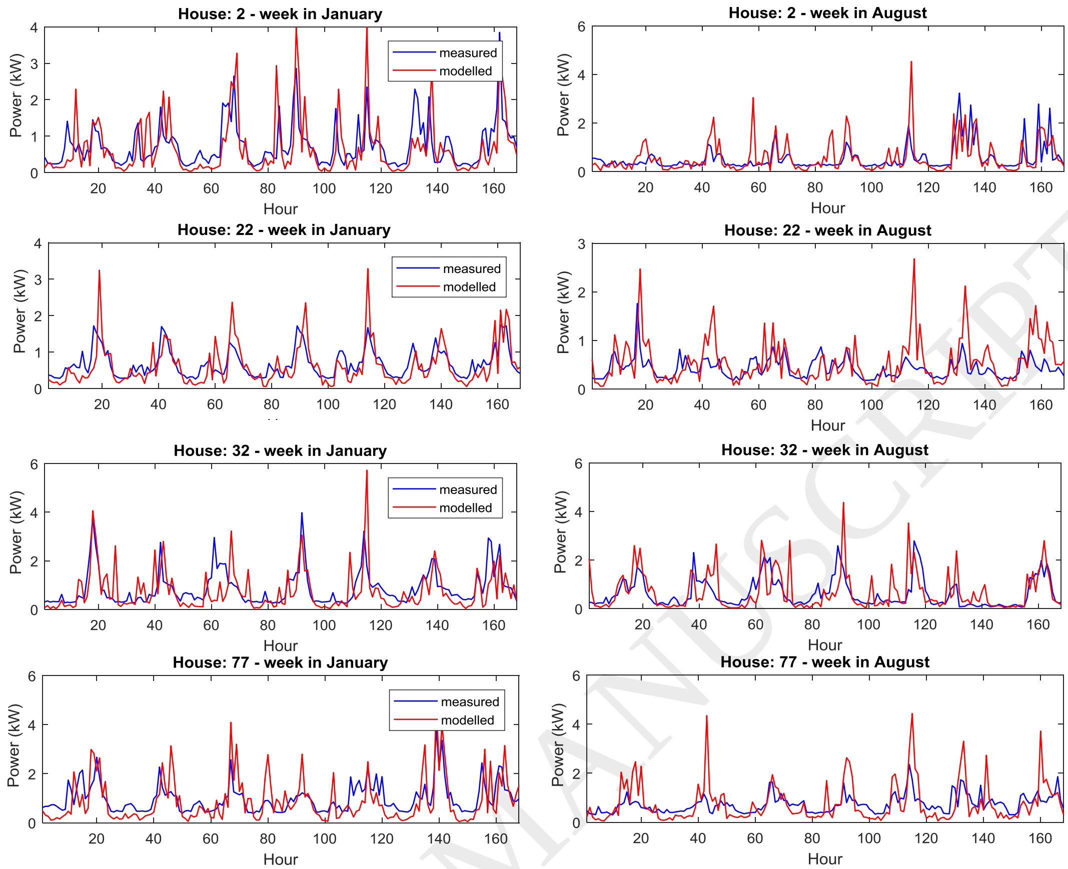


Fig. 5 Modelled and measured end-use load profiles in four households during a winter and summer week.

The correspondence between the modelled and measured data can be also expressed by Normalized Variation Factor (NVF) also used by (Borg & Kelly, 2011; Capasso, Lamedica, Prudenzi, & Grattieri, 1994; Widén, Lundh, et al., 2009). The NVF is the squared sum of the difference between the modelled (E_{mod}) and the measured energy demand, normalized by the mean squared measured energy load of every time step and can be calculated using the Eq.5. The smaller the NVF is achieved the better match between the modelled and measured values.

$$NVF = \frac{\sum_i^n (E_{mod}(i) - E_{meas}(i))^2}{n(\bar{E}_{meas})^2} \qquad (6)$$

The NVF has primarily been used to compare the end-use load curves of the specific appliance, however, in this study it is being used to quantify how closely the modelled total demand values follow the measured data. The hourly average NVF values vary between the 0.49 and 3.01 for different households with an average hourly NVF for the all households of 1.23. The high NVF values are for the households where the annual electricity demand is lower than 1600 kWh/year. If following the assumption of 1600 kWh/year per occupant, these houses should be modelled with less than 1 occupant, which is not feasible. A way to solve this issue could be to replace the current appliances with more efficient ones. The low NVF values are comparable with results from (Borg & Kelly, 2011).

As shown in Fig. 6 the annual electricity consumption calculated based on the 1-minute output profiles yields results which are in a very good correspondence with the output of the measurement campaign conducted in 8500 Danish single family houses (Nærvig-Petersen & Gram-Hanssen, 2005). More than 95% of the modelled annual electricity consumption values are with the given range.

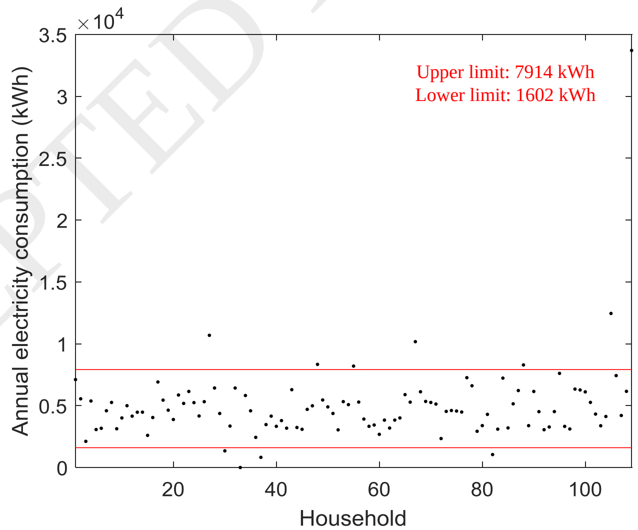
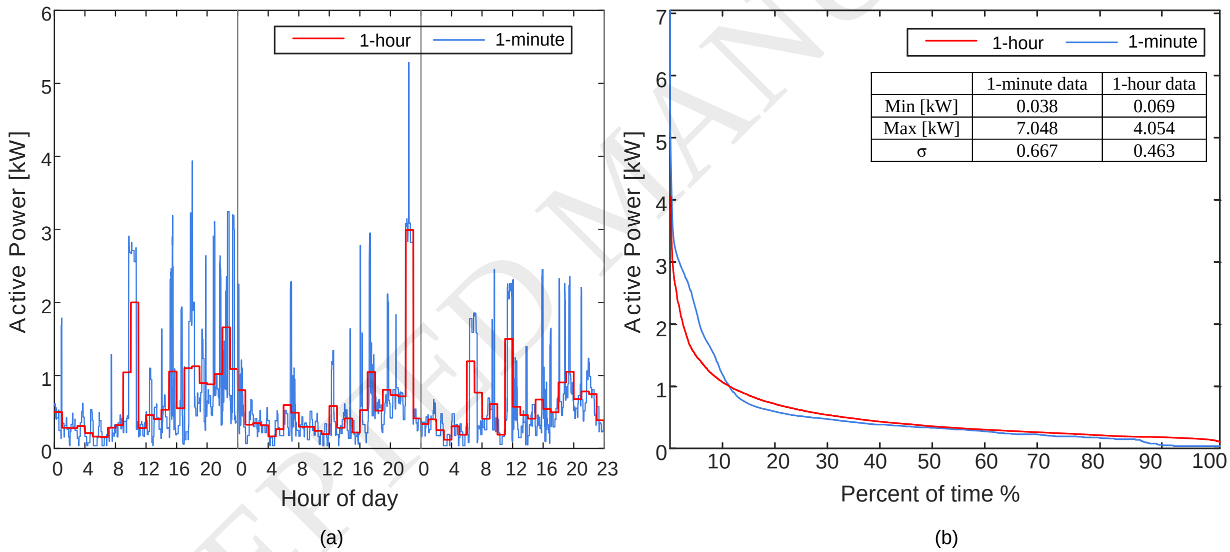


Fig 6. Annual electricity demand in all households with the upper and low limits based on [Sbi2009:05]

As shown in Fig. 7 the resolution of household load profiles changes the message of occupants' electricity use given to utilities and network planning engineers. Although the 1-hour data reflect well the overall trend, it fails to capture the characteristic spikiness of electricity demand, which is of special interest for network operators. The load duration curves and standard deviations indicate that 1-hour data has a more uniform distribution, and the high-end as well as the low-end power peaks are underestimated compared to the 1-minute distribution. Moreover, with low time-resolution data, it is very difficult to recognize which appliances are used at specific time; hence, development of correct demand control strategies applicable for the future stable network operation becomes more complex.



	1-minute data	1-hour data
Min [kW]	0.038	0.069
Max [kW]	7.048	4.054
σ	0.667	0.463

Fig. 7 a) Household BL profile in different resolutions for three weekdays in first week of January; b) Load duration curve of 1-minute and 1-hour data

5. Performance evaluation of LV network

In Figs. 8 and 9 the network performance is represented for 1-hour and 1-minute base load profiles for a winter week in January. In the 1-hour modeling approach, the network performs within the required limits. However, increasing the resolution of input data gives a different message, i.e. the loading of the transformer station (Lst) exceeds the limit for stable operation and it reaches 0.82 p.u. during the Friday morning peak. The maximum loading of the power line

(Llmax) is almost at the limit with value of 0.73 p.u. Moreover, on Tuesday evening the instantaneous power consumption of different consumers in the LV network is synchronized leading to the short-term violation of the under-voltage limit, in this case the Vmin reaches the value of 0.922 p.u.

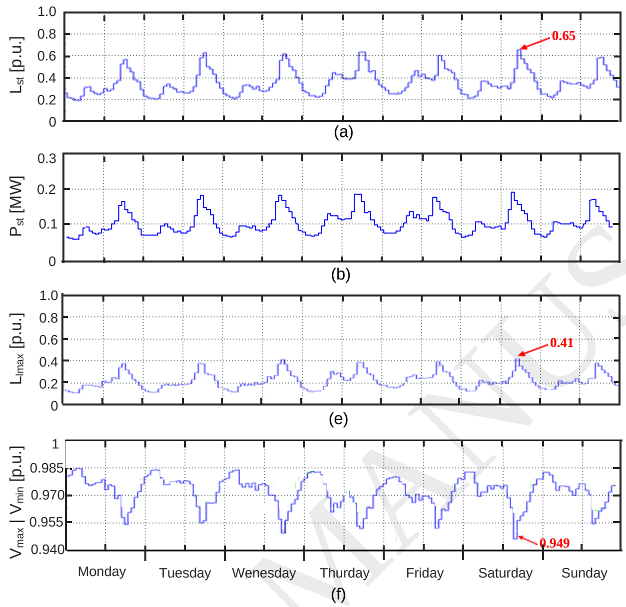


Fig. 8 LV network performance for a week in January for 1-hour data, (a) L_{st}, (b) P_{st}, (e) L_{lmax}, (f) V_{max} and V_{min}.

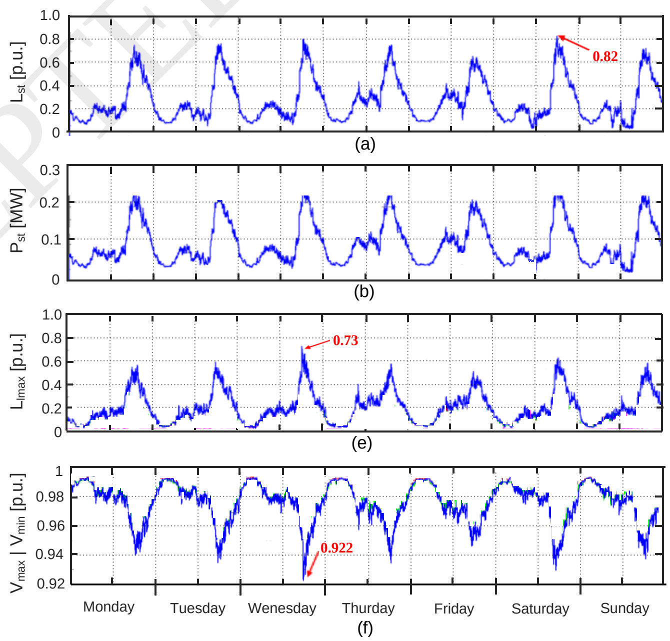


Fig. 9 LV network performance for a week in January for 1-minute data, (a) L_{st}, (b) P_{st}, (e) L_{lmax}, (f) V_{max} and V_{min}.

Since the seasonality significantly influences the load and generation in Denmark, a winter and summer cases are compared in the analysis. Therefore, as it is illustrated in Figs. 10 and 11, the network performance is represented and compared for the three selected scenarios for a winter week in January and summer week in August.

In the winter case, one of the first things to be noticed is how the loading of the ST already in case I reaches close to unacceptable points of operation, such as a loading peak of 0.789 p.u. obtained during the evening peak of Wednesday. It is interesting to see how its loading substantially increases as the penetration level of prosumers increases, reaching a loading peak (Lst) of 0.918 p.u. during the same period of time. This phenomenon, which is a consequence of the demand growth represented by the presence of HPs in the system, is highlighted in the early hours of Friday, Saturday and Sunday. As it shown in Fig. 10.b, another aspect derived from the presence of PVs is the reverse power flow. As the irradiation in Denmark during winter is rather low in average, for this time of the year, this effect is expected to become a challenge only if the estimations made by the DEA for 2050 are satisfied (case III). For case II, since the PV power generated is still limited, no reverse power flow is foreseen, meaning the energy produced is distributed locally and consequently reduces the loading of the ST and underground cables during those moments. However, for case III, since the local energy balance capacity might not be sufficient during local generation moments, the stress of the infrastructure is expected to increase in respect to the previous case due to the reverse power flow, see Thursday and Friday. Paying a bit attention to the maximum and minimum voltage profiles derived from the different study cases proves that various aspects are worth to be elaborating.

. First, it is observed on Tuesday that the instantaneous power consumption of different consumers in the LV network could be synchronized leading already to the violation of the under-voltage limit during the peak moments of the day, in this case the V_{min} reaches the value of 0.931 p.u. In future presence of prosumers, this effect could be aggravated due to the voltage drop originated by the additional power required to supply HPs, getting to under-voltage levels of 0.922 p.u. like the one shown in case III. Secondly, in the same case scenario, it is relevant to elaborate about the voltage-event occurred during Thursday since it introduces a new challenge that DSO should face in the coming future. Due to PV infeed after midday the Vmax reaches the value 1.048 p.u. and after some hours Vmin gets to 0.939 p.u.. Even though the achieved maximum and minimum values of the voltage across LV network are still within the stipulated limits, the difference between them - relative voltage change - becomes larger than 10% allowed within a day for the same customer. This characteristic situation is expected to happen more and more frequently in those LV networks penetrated by prosumers, which lack equilibrium between load and installed capacity of generation and also face problems with synchronizing their individual actuation moments.

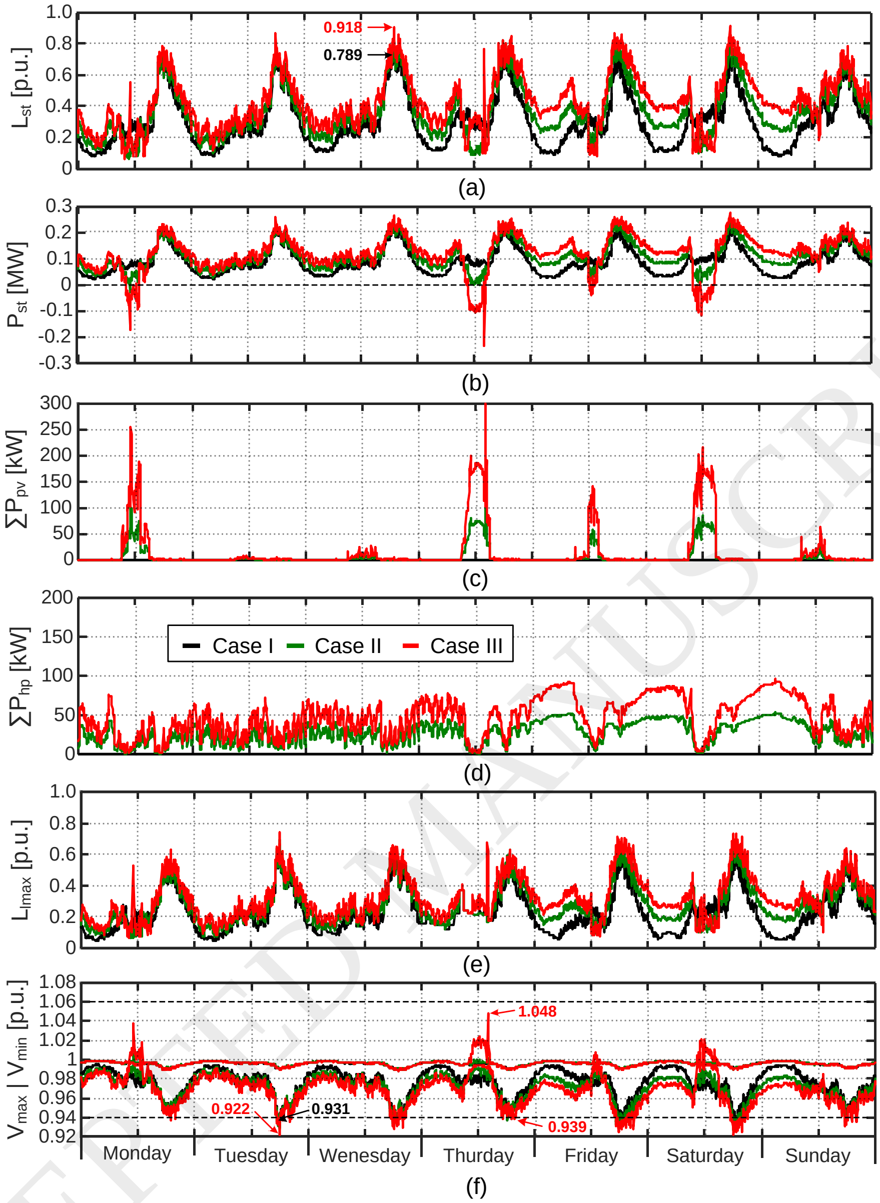


Fig. 10 Results for a week in January: (a) L_{st}, (b) P_{st}, (c) ΣP_{pv}, (d) ΣP_{hp}, (e) L_{lmax} and (f) V_{max} and V_{min}

In the summer case instead, the maximum loading of the ST (Pst) is currently around 0.633 p.u., which is achieved during the Friday evening peak. In comparison with the winter illustration, the maximum loading point becomes lower which is reasonable since in average the electricity consumption in Denmark is lower in summer than in winter. Taking this aspect into consideration plus the fact that prosumers have lower HP consumption but significant PV power is generated, a LV grid energy balance gets unbalanced consequently creating an extensive reverse power flow out of the grid.

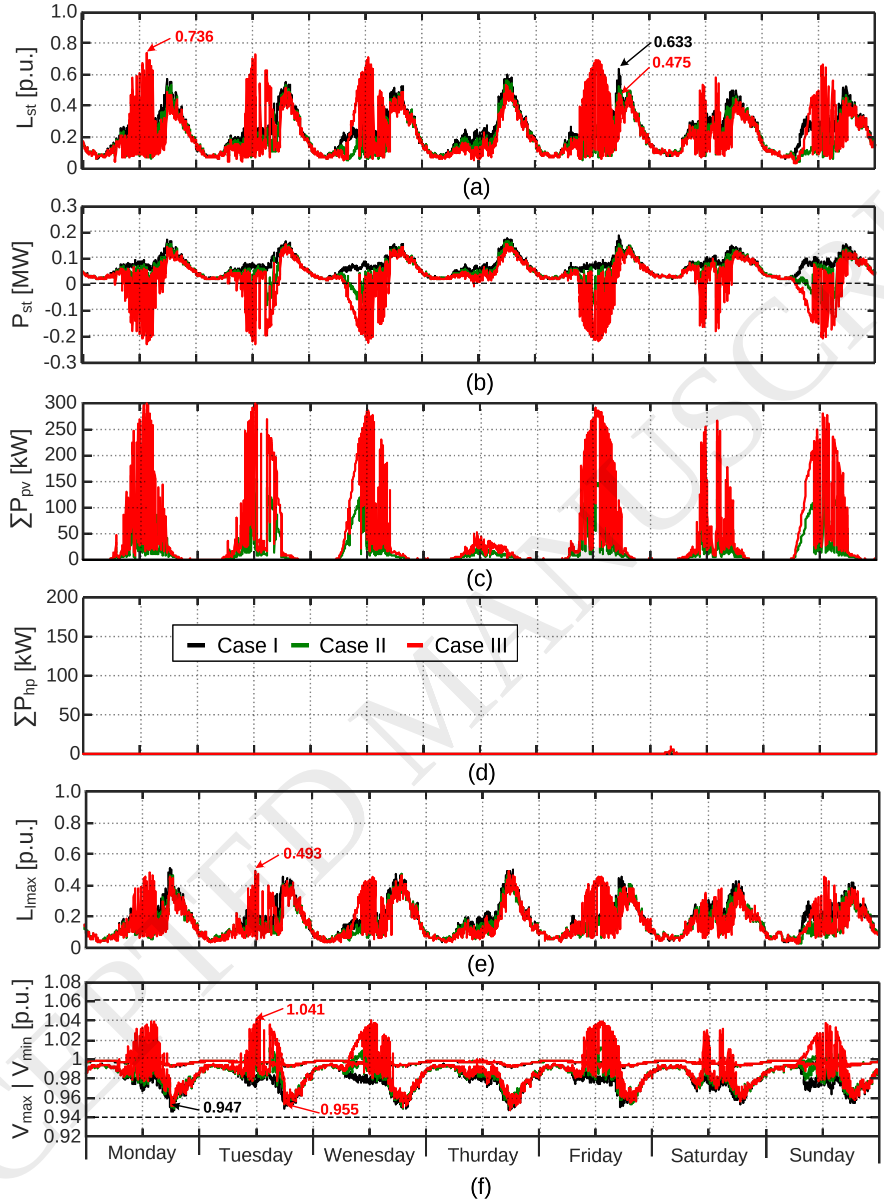


Fig. 11 Results for a week in August: (a) L_{st}, (b) P_{st}, (c) ΣP_{pv}, (d) ΣP_{hp}, (e) L_{lmax} and (f) V_{max} and V_{min}.

Therefore, the reason for maximum loading of the ST is not represented by the peak system demand but by the peak PV generation. In this case, this value is 0.736 p.u. and is obtained for case III after midday on Monday. Similarly, what has been stated for the ST can be extrapolated to the loading of the underground cables, as shown in Fig. 11.e. All these aspects clearly highlight the fact that in the future the DSO should expect that the loading of the infrastructure will have different natures and will occur in a different moment of the day in comparison to how this is happening nowadays. In relation to the voltage for this period of the year, it is clear that nowadays every bus of the local network is supplied with a voltage that is within the stipulated limits. Nevertheless, considering the future scenarios there are two major events to be elaborated on as seen in the results obtained. On the one hand, the violation where the relative voltage change becomes larger than the 10 % allowed within a day is expected to appear much more frequently during the summer months. On the other hand, due to the unsteadiness of the PV generation mainly originated by the sun-blocking factor of clouds, fast voltage changes might be induced in specific buses of the LV network, especially in those more remotely located. As a consequence, the risk for originating disturbances such as flicker at the user level increases significantly.

6. Conclusions

As a consequence of the energy supply reconversion and the heating system electrification, a growth in the number of prosumers is expected in Danish LV distribution networks. These prosumers, which are frequently characterized by being heated with HP units and having their own PV installation, are expected to strongly influence the performance of the local distribution systems in the coming future. Therefore, precision becomes essential for DSOs not only in representing power consumption/generation of prosumers during the system studies but also to appropriately evaluate and understand their future behavior. Therefore, this paper presents the transformation procedure, which enables generating 1-minute based consumption profiles from hourly readings delivered by electricity supplier. The methodology is shown to make realistic reproductions of 1-hour electricity demand profiles for individual customers and to generate well-corresponding 1-minute load profiles reflecting the effects of individual appliances power cycle. The modelled and measured data present high correspondence for most cases, the shortcoming of the proposed methodology is the households with very low annual electricity consumption. However, according to (Nærvig-Petersen & Gram-Hanssen, 2005), Danish households with such low electricity use constitute less than 5% of the single family houses. The value of the proposed methodology is that it is cheap and straightforward and can be easily applied by the DSOs, utilities or any actors/stakeholders involved in management of smart and suitable cities and/or communities.. The paper also presents a framework for accurate power system impact analysis of the residential LV networks. The obtained results illustrate the current and future dynamic operation of the LV systems for two critical weeks during the year, with highest load and distributed generation, respectively, and define the major challenges that network planning engineers should focus on when providing solutions for secure and uninterrupted system operation. It also reveals that more attention must be given to the urban planning of future sustainable residential communities, if all new houses are to be designed as prosumers, which actually will be the requirement in Denmark in 2020.. Finally, the results strongly highlight the need for application of the demand respond programs and active engagement of the customers/homeowners in the successful transition towards well operating fossil free and sustainable society of the future. Therefore, demand response analysis together with inclusion of household storage systems, which might be useful in other countries than for the Danish case and which is missing in this paper, are obvious focus points for future extensions of the presented work.

The created framework can be easily applied to evaluate the influence of different means, e.g. control signals, demand respond programs, coordination mechanisms, which can contribute in solving the operational bottlenecks of future LV networks and in general suistanable communities. The authors acknowledge that the selected LV network is not a generic network, but the Danish LV network structure match very well with standard generic LV grids from IEEE and CIGRE and are therefore representative for residential LV networks in the same manner as the standard generic grids.

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APPENDIX

Table A1 – Line parameters for the LV network

Name of the line	**R [Ω/km]**	**X [Ω/km]**
S3C01,S3C02,S3C03,S3C04,S3C05,S3C06,S3C07,S3C11	0.208	0.052
S3C08,S3C09,S3C10,S3C20,S3C21,S3C22	0.32	0.054
S3C15,S3C16,S3C17,S3C18,S3C19,S3C23	0.641	0.058
S1C08,S1C09,S1C10,S1C11,S2C15,S2C16,S2C17,S3C24,S3C25, S1C01,S1C02,S1C03,S1C04,S1C05,S1C06,S1C07,S1C12,S2C01,S2C02,S2C03,	0.641	0.072
S2C04,S2C05,S2C06,S2C07,S2C08,S2C09,S2C10,S2C11,S2C12,S2C13,S2C14, S2C18,S3C12,S3C13,S3C14,S4C01,S4C02,S5C01,S6C01,#8,S7C01	0.208	0.068
S3C26	0.32	0.07
S3C26#1	1.91	0.094
S3C26#2	1.83	0.097
S3C26#3, S3C26#4	3.08	0101
S3C26#5	0.641	0.72
S3C26#6	1.2	0.075
S3C26#7	0.32	0.07

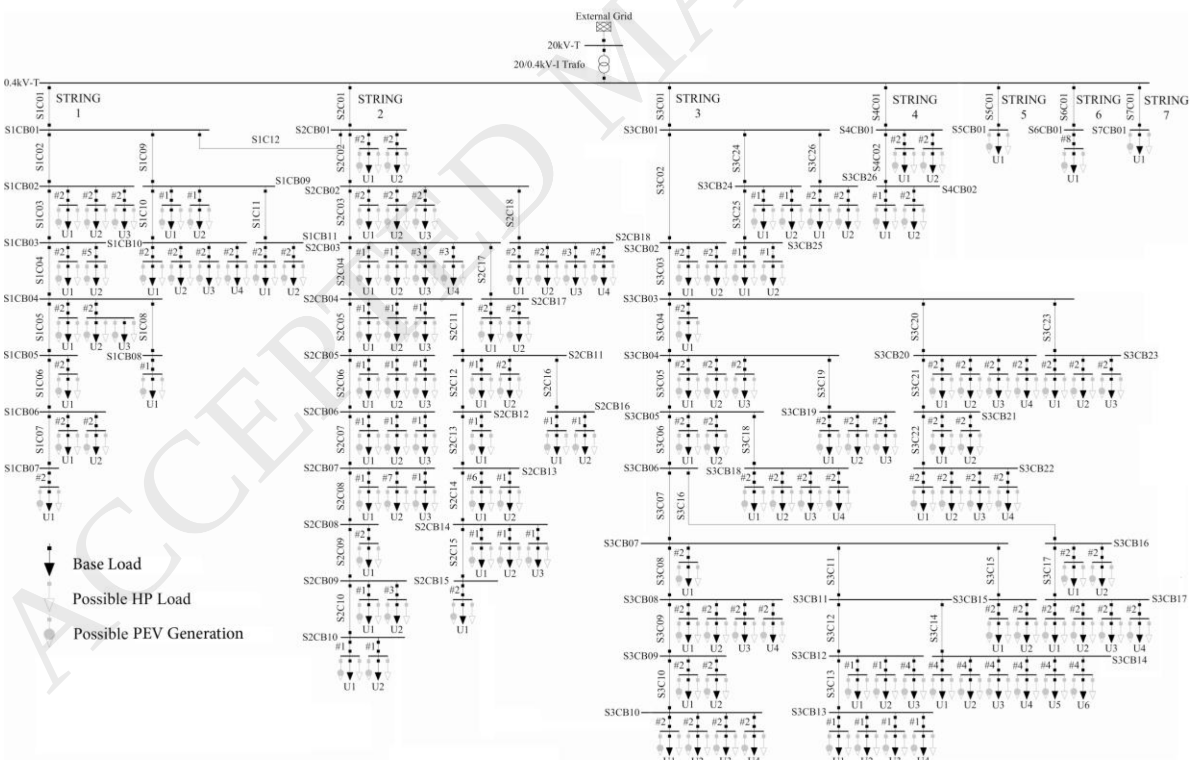

Fig. A1. 196 Bus 0.4 kV LV grid.